THE EFFECTS OF COLLISIONS AND DYNAMICAL EXCITATION ON THE COMPOSITION OF GROWING TERRESTRIAL PLANET EMBRYOS Philip. J. Carter[1], Zoë. M. Leinhardt[1], Tim Elliott[2], Michael J. Walter[2] and Sarah T. Stewart[3], [1]School of Physics, University of Bristol, H. H. Wills Physics laboratory, Tyndall Avenue, Bristol BS8 1TL, UK (p.carter@bristol.ac.uk), [2]School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK, [3]Department of Earth and Planetary Sciences, University of California, Davis, CA 95616, USA.

Introduction: The notion that the Earth has chondritic relative abundances of refractory lithophile elements has recently been brought into question, e.g. [1]. Several studies have suggested that the collisions involved in planetary accretion may inevitably lead to non-chondritic compositions, e.g. [2, 3], the stripping of crust and mantle via collisions between differentiated bodies leading to the compositional differences seen in the solar system today.

This idea has now begun to be explored in detail using *N*-body models of terrestrial planet formation e.g. [4, 5]. These first studies were concerned only with the calmest scenario possible, in which the terrestrial region is unperturbed by giant planets. Since higher impact energies are likely to lead to more erosion of material from growing planet embryos, the dynamics of the disc may have a significant effect on planetary compositions. Migration of the giant planets has been invoked in the form of the Grand Tack model [6] to explain Mars's small size and depopulate the asteroid belt. This scenario presents a dynamically active picture of the early solar system that may have important consequences for collisional erosion during accretion of the terrestrial planets.

We report the results of *N*-body simulations of the intermediate stages of planet formation that explore these two contrasting dynamical scenarios using a state-of-the art collision model, and examine the change in the Fe/Mg ratio of the embryos formed from initially chondritic planetesimals.

Numerical Method: We use a modified version of the parallelized *N*-body code PKDGRAV [7, 8] to model the gravitational interactions of planetesimals in orbit around a star. A state-of-the-art collision model [9,10] has been incorporated into this code to calculate the outcomes of collisions, including partial accretion, hit-and-run and erosive impacts.

The differentiated planetesimals are modeled with independently tracked core and mantle components, which can be modified by collisions according to the mantle stripping laws from [11]. This allows the evolving core mass fractions of every object to be tracked as the initial 100,000 ~200 km planetesimals accrete through runaway and oligarchic growth to form planetary embryos.

We model Jupiter's migration by giving it an additional acceleration to match the velocities used by [6]. Unlike other Grand Tack simulations, we begin with a less evolved planetesimal disc and allow some growth to occur before Jupiter starts migrating. We ignore Saturn and the ice giants as [6] found they had little effect on the inner disc.

We refer to two timescales in this work, the internal simulation time, and the effective time that the simulations represent, see [12] for more detail.

Results: Jupiter's migration shepherds many planetesimals inwards and excites their orbits. The Grand Tack leaves eccentricities in the inner disc significantly higher than in the calm simulations, and leaves the planetesimal disc much more mixed. Embryo growth in the calm simulations is very similar to that seen in previous studies e.g. [13].

Examining the types of collisions that occur in the simulations (Fig. 1), it is clear that the Grand Tack causes a significant increase in the fraction of erosive impacts (yellow) and supercatastrophic disruptions (red) compared to the calm disc. These collisions can strip large amounts of mantle from the target body, and even excavate material from the cores, allowing Fe to

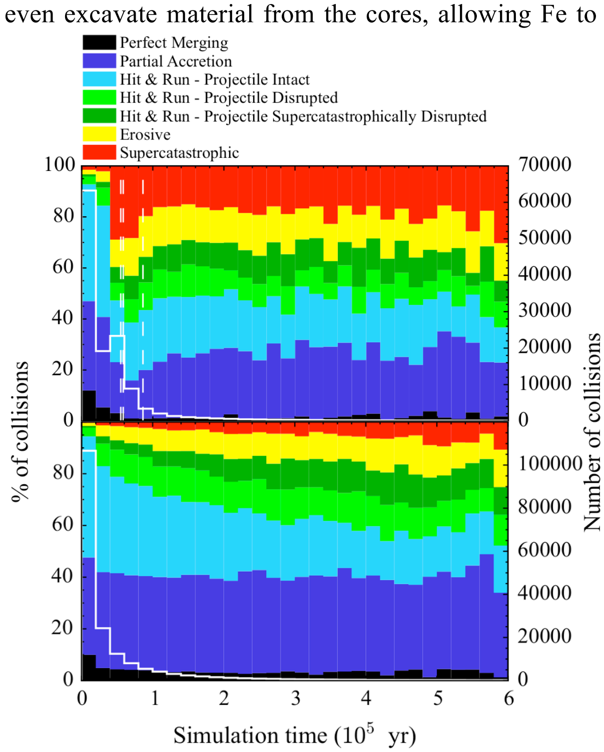

Fig. 1: Collision history for Grand Tack (top) and calm disc (bottom) simulations. Coloured histograms show the percentage of each collision type per time bin (left axes), and the white lines show the total number of collisions in each bin (right axes).

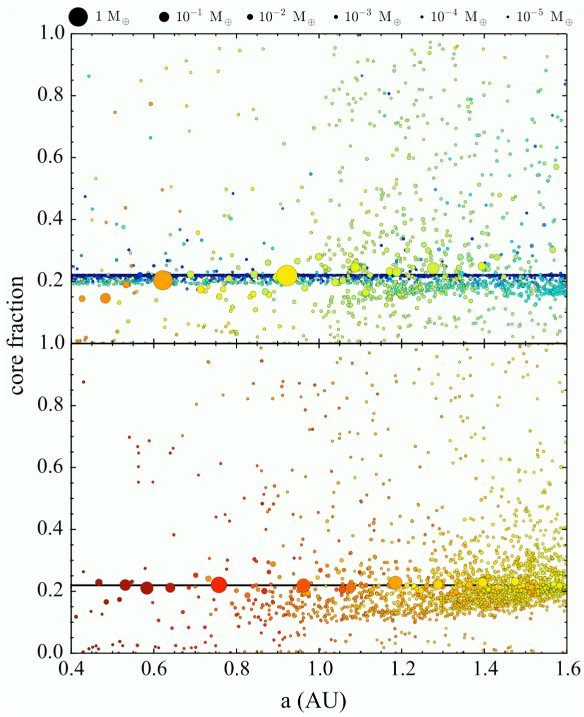

Fig. 2: Core mass fractions of planetesimals and embryos at the end of Grand Tack (top) and calm disc (bottom) simulations. The colours of bodies indicated their mass-weighted radial source composition, showing the degree of mixing. The solid line shows the initial planetesimal core fraction.

be redistributed to other bodies.

Our simulations show that the collisions occurring in the protoplanetary disc during the growth of planetary embryos naturally lead to some variation in the core fractions of those embryos compared to the uniform starting value (see Fig. 2). The variation in embryo core fractions after ~20 Myr effective time is greater under the influence of a migrating Jupiter than in a calm, unperturbed disc. It is also clear from Fig. 2 that the smallest planetesimals remaining at the end of our simulations show a huge variation in core fraction, with some remnants composed entirely of silicate mantle, and some entirely of iron.

Bulk compositions of planetary embryos: In order to estimate the Fe/Mg ratios of the resulting embryos we apply these change in core mass fraction to material spanning the range of chondritic meteorite compositions. A metallic core of the proscribed initial mass is formed, and the resulting mantle composition calculated for each chondrite type. The final core and mantle mass fractions for embryos found in the simulations are then applied to determine final bulk Fe/Mg ratios. Finally, we apply the additional constraint that the resulting embryo must have sufficient Fe to match Earth's core masss fraction. See [12] for more detail.

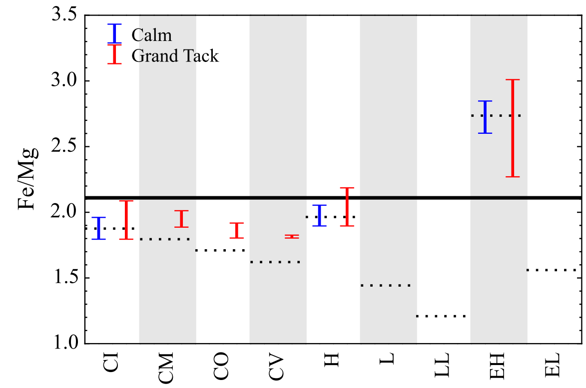

Fig. 3: Fe/Mg ratio ranges for embryos accreted from particular chondrites (with initial core fractions of 0.22) allowing reequilibration to match the Earth's core fraction of 0.32. The dashed lines are the primitive values for each chondrite and the solid black line represents bulk Earth. Neither of the simulations shown is able to produce an embryo with sufficient Fe to match Earth's core from L, LL or EL chondrites.

Fig. 3 shows the differences between the starting chondritic compositions (dashed lines), and bulk Earth (solid line) [3], with the ranges of Fe/Mg resulting from two of our simulations (coloured bars). It is clear that collisional processing can produce embryos that match Earth's Fe/Mg ratio in some cases.

Conclusions: The collisions of planetesimals and embryos during runaway and oligarchic growth naturally lead to compositional variations that could account for the Earth's non-chondritic bulk composition. Regardless of whether the compositional shift makes the Earth appear more chondritic or less chondritic, it is clear that collisions could substantially alter the composition of embryos from that of the differentiated planetesimals from which they accreted.

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